Comparison of PAM-4 and NRZ Signaling

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History and Perception

- NRZ is the incumbent signaling method for 3 Gbps and 6 Gbps generations of electrical standards.

- Optimal solution for 10-12 Gbps generations of standards currently being investigated. Factors include:

  - Complexity of silicon (equalization, signalling method)

  - Complexity of channel design (backplane, connectors)

    - Market is fragmented into vendors assuming Greenfield channels and vendors that want to use legacy designs.

  - Power dissapation (of silicon -- but higher loss channels will require more power dissapation in silicon)

History and Perception

- Popular perception is that PAM-4 signalling enables use of legacy backplanes and interconnect.
- More detailed analysis of NRZ and PAM-4 signalling methods shows that reality is more complex:
  - PAM-4 does not universally guarantee that legacy backplane designs will be usable.
  - NRZ is not universally excluded from serving legacy designs.

Points of Comparison

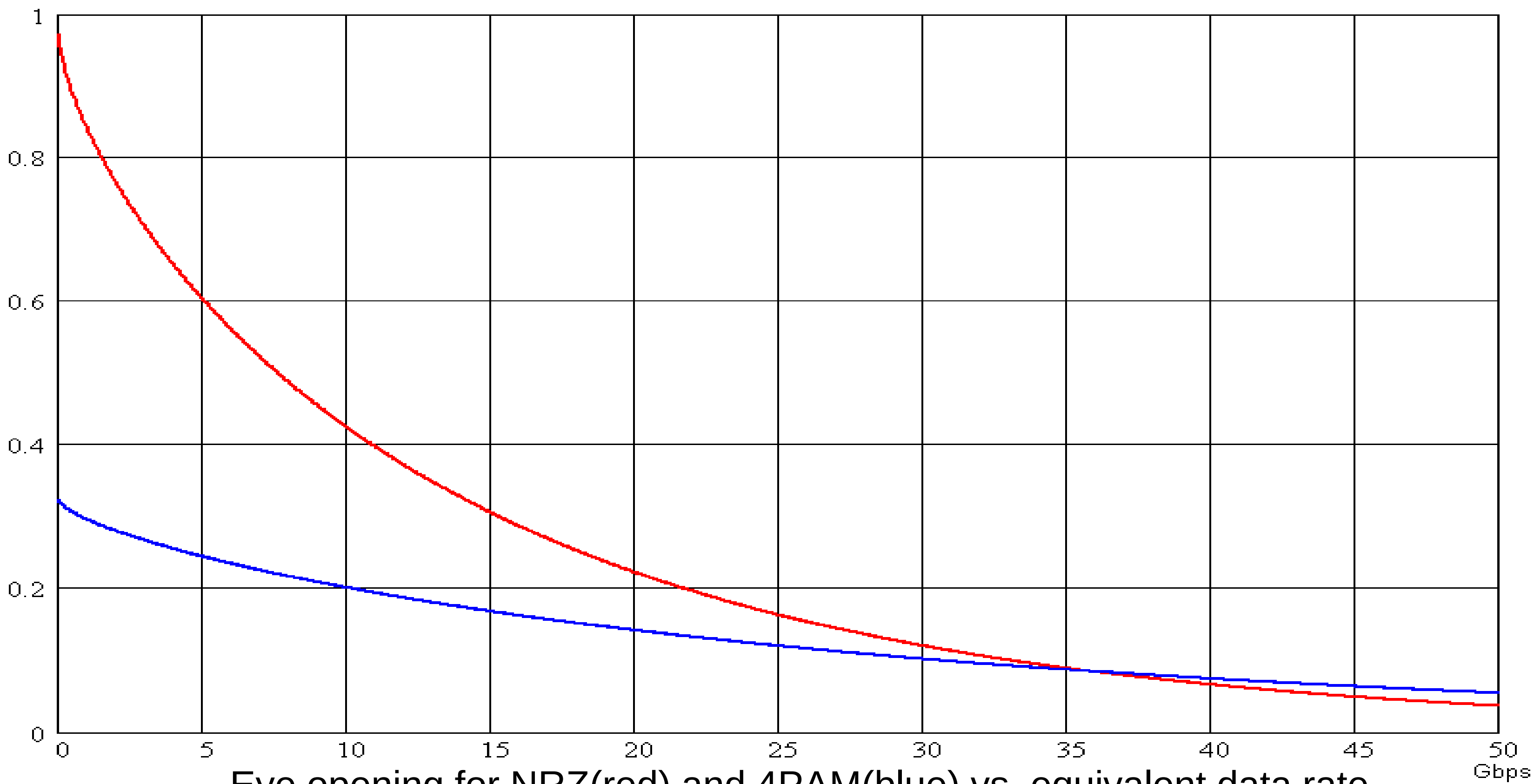
- **NRZ and PAM-4 are compared on the following points:**
  - **Vertical Eye Opening (Differential Amplitude)**
  - **Horizontal Eye Closure (Unit Interval minus Jitter)**
  - **Crosstalk Budget (Difference between amplitude of Noise Aggressor and Signal of Noise Victim)**
  - **Power Analysis**

Vertical Eye Opening Comparison

- PAM-4 vs. NRZ factors effecting vertical eye opening:
  - Channel loss rises with frequency
    - Lower baud rate of PAM-4 implies less loss in channel
  - PAM-4 launch amplitude per signal level is 33% of NRZ for equivalent driver technology and supply voltage
- At lower frequencies: Higher launch for NRZ provides greater vertical eye opening.
- At higher frequencies: Lower loss for PAM-4 (because baud rate is 1/2 that of NRZ) compensates for lower launch voltage and results in greater vertical eye opening.

Vertical Eye Opening Comparison

- Transmission line analysis shows expected crossover above 35 Gbps.
  - ►NRZ results in bigger eye below crossover (range of current interest)
  - ►PAM-4 results in bigger eye above crossover



Eye opening for NRZ(red) and 4PAM(blue) vs. equivalent data rate for 26" transmission line. (Source: Acuid Corporation)

PAM-4 Implementation Notes

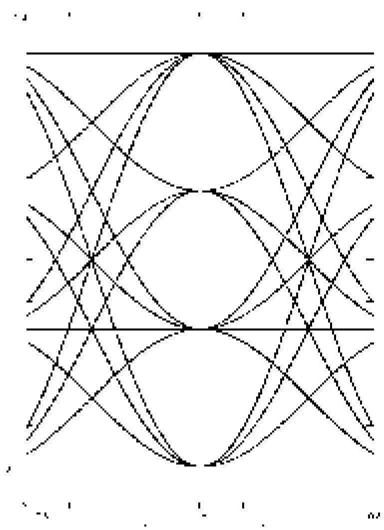
- **Previous comparison assumes similar silicon technologies and power supply voltages for the NRZ and PAM-4 implementations.**
- **Many existing PAM-4 implementations use higher power supply voltages to increase the total available dynamic range.**
- **Advantages:**
  - **Increased transmit eye amplitude**
- **Disadvantages:**
  - **Increased power dissapation**
  - **May require use of dual-oxide devices in silicon implementation**
- **Note: NRZ can also increase transmit amplitude to enable operation on lossy channels.**

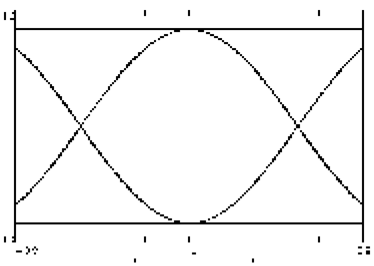
Horizontal Eye Opening Comparison

- **PAM-4 vs. NRZ factors effecting horizontal eye opening:**
  - **Lower baud rate means more eye width due to base cycle.**
  - **DJ/RJ at the transmitter are related to spectrum of the transmitted signal and tend to scale with baud rate.**
    - **Implies that absolute value of DJ/RJ for half baud rate design would be 2x that of full baud rate design.**
    - **With careful design should be able to achieve DJ/RJ for half baud rate design of 1.8x that of full baud rate design.**
  - **Base cycle minus DJ/RJ still results in larger horizontal eye opening for PAM-4 .... if these were the only factors ....**

Horizontal Eye Opening Comparison

- **PAM-4 vs. NRZ factors effecting horizontal eye opening:**
  - **PAM-4 results in additional loss in 33% of eye width due to switching between adjacent and non-adjacent levels.**





Horizontal Eye Opening Comparison

- **PAM-4 vs. NRZ factors effecting horizontal eye opening:**
  - **Combination of effects will result in larger horizontal eye opening for a PAM-4 solution at transmitter output.**
    - ***But eye opening for PAM-4 is <u>not</u> twice as large as NRZ as would be implied from baud rate difference.***

	NRZ	PAM-4
Total Cycle (11.1 Gbps)	90 ps	180 ps
Total Jitter	(0.30 UI) 27 ps	(0.27 UI) 48 ps
Loss in Eye Width for PAM-4	0 ps	(0.33 UI) 60 ps
Eye Opening at Tx	(0.70 UI) 63 ps	(0.40 UI) 72 ps

Horizontal Eye Opening Comparison

- **PAM-4 vs. NRZ factors effecting horizontal eye opening:**
  - **Eye width reduction at Transmitter due to PAM-4 switching between adjacent and non-adjacent levels is effectively a form of deterministic jitter.**
  - **Spectrum of this jitter component is near the frequency of the baud rate, substantially above the bandwidth of the channel.**
  - ***Transmit jitter with this spectrum is particularly susceptible to phase noise amplification by the channel.***

PAM-4 Implementation Notes

- Previous comparison assumes no special encoding of data to overcome limitations of signalling technique.
- Many existing PAM-4 implementations use coding to limit or eliminate transitions between non-adjacent levels.
- Advantages:
  - Increased eye width due to reduction/elimination of non-adjacent transition effect.
- Disadvantages:
  - Coding requires overhead (~25% typical) and thereby requires higher baud rate to achieve same bit rate.
  - For 25% overhead, net improvement in eye width is ~ 0.13 UI.
- Note: NRZ can also increase use coding to set minimum run length to control spectral content of signal and thereby reduce frequency dependent losses in channel.

Crosstalk Concerns

- Crosstalk is a substantial contributor to jitter at the receiver.
- PAM-4 maximum signal swing is similar to NRZ and therefore the noise level from the aggressor signal is the same for both PAM-4 and NRZ.
- PAM-4 vertical eye opening is 33% of NRZ and therefore the victim signal's tolerance for crosstalk is less.
- Crosstalk budget for PAM-4 therefore starts out 9 dB less than for NRZ.
- Greater channel attenuation at higher frequencies reduces this advantage for NRZ to the 3-6 dB range (depending on channel design).

Power Concerns

- **Power analysis is based on implementation experience in TSMC 0.18 um and 0.13 um CMOS.**
- **PAM-4 provides power savings for Tx/Rx circuits over NRZ:**
  - **3:1 ratio of PAM-4 Tx/Rx circuits to NRZ Tx/Rx circuits**
  - **Each circuit operates at 1/2 baud rate and uses 1/3 the power (average dependent on circuit design)**
  - ***Net is PAM-4 Tx/Rx uses same power as NRZ Tx/Rx***
- ***Assumes equivalent power supplies***
- ***Assumes equivalent power utilization by equalization circuits***

Power Concerns

- **PAM-4 systems generally use larger power supply voltages to overcome vertical eye disadvantages.**
  - **Increase in launch amplitude results in power dissapation increase (placing PAM-4 at a power disadvantage).**
- **To achieve equivalent power dissapation, less complex equalization scheme must be assumed for PAM-4.**
  - **Equivalent equalization schemes require significant increase in power dissapation for PAM-4 vs. NRZ due to implementation complexity (placing PAM-4 at a power disadvantage).**
  - **PAM-4 with DFE is also undesirable due to DFE error propagation considerations.**
- **Techniques used to improve performance of PAM-4 carry significant power penalities, negating any power advantage of PAM-4.**

Statistical Eye Analysis

- Statistical Eye Analysis technique is described in [2].
  - Algorithm uses S-parameter measurements of a channel along with ideal transmitter and receiver models to determine whether the channel can pass a receivable signal.
  - Algorithm selects optimal coefficients for transmit pre-emphasis and the receiver filter, and then uses statistical techniques to determine the resulting eye opening after receiver equalization.

Statistical Eye Analysis (Assumptions)

- Goal of this analysis is to compare an NRZ solution to a PAM-4 solution of approximately equivalent complexity and power dissapation.

- Performed analysis using 5 backplanes:
  - Four backplanes are existing backplanes from various companies designed for 10 Gbps demonstration.
  - One legacy backplane (backplane E).

- Equalization assumptions (based on existing best-of-breed for each signalling technique):
  - NRZ with preemphasis and 4-tap DFE
  - PAM-4 with linear equalization

- Similar supply voltage for both NRZ and PAM-4 drivers is assumed (i.e. signal swing for each PAM-4 signal level is 33% of NRZ case).

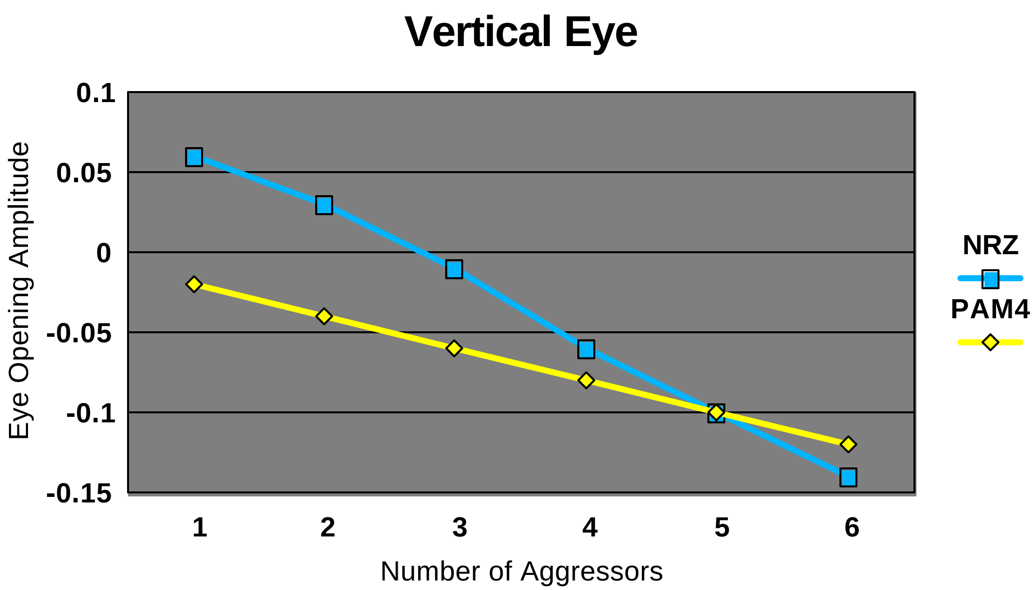
Statistical Eye Analysis (Pass/Fail Criteria)

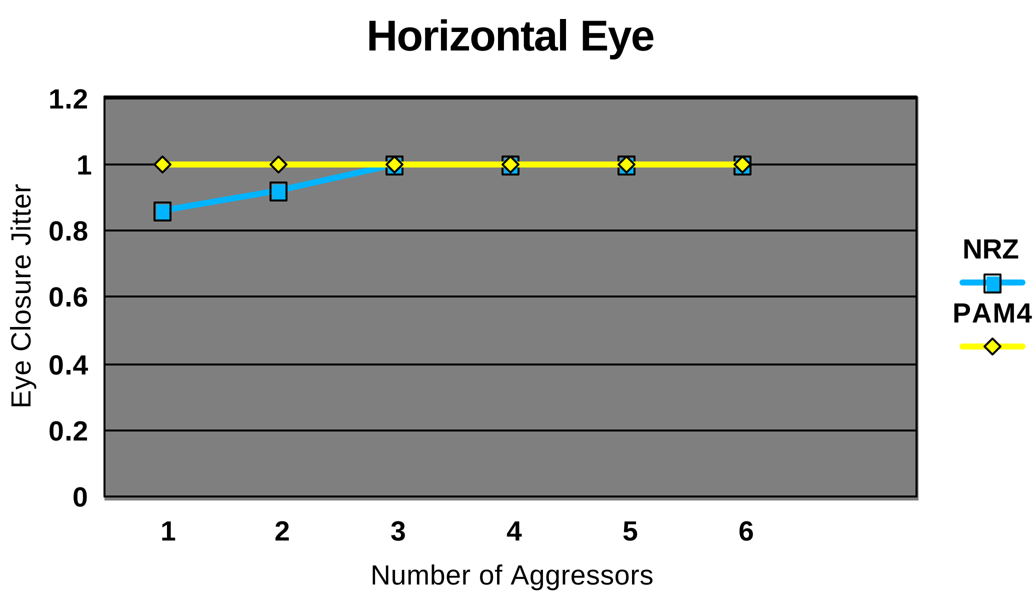
- Analysis performed for 1 to 6 crosstalk aggressors.

- Pass / Fail Criteria:
  - Amplitude is open if > 0.0 V
  - Jitter is okay if < 0.90 UI

- NRZ and PAM-4 cases can be compared by determining number of crosstalk aggressors at which one or both of the pass/fail criteria indicate failure.

Backplane A Results





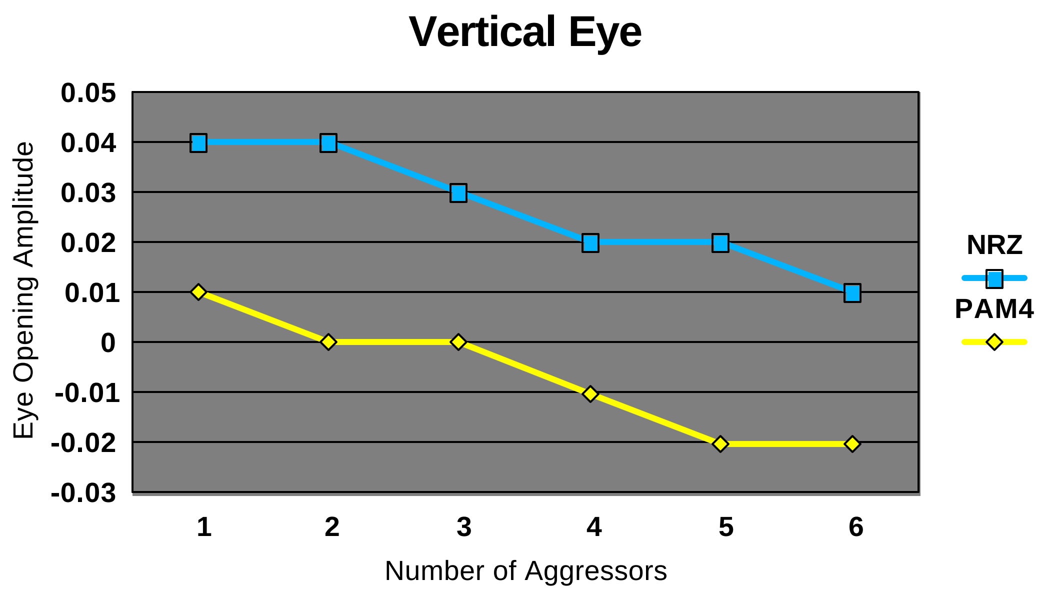
NRZ Eye:

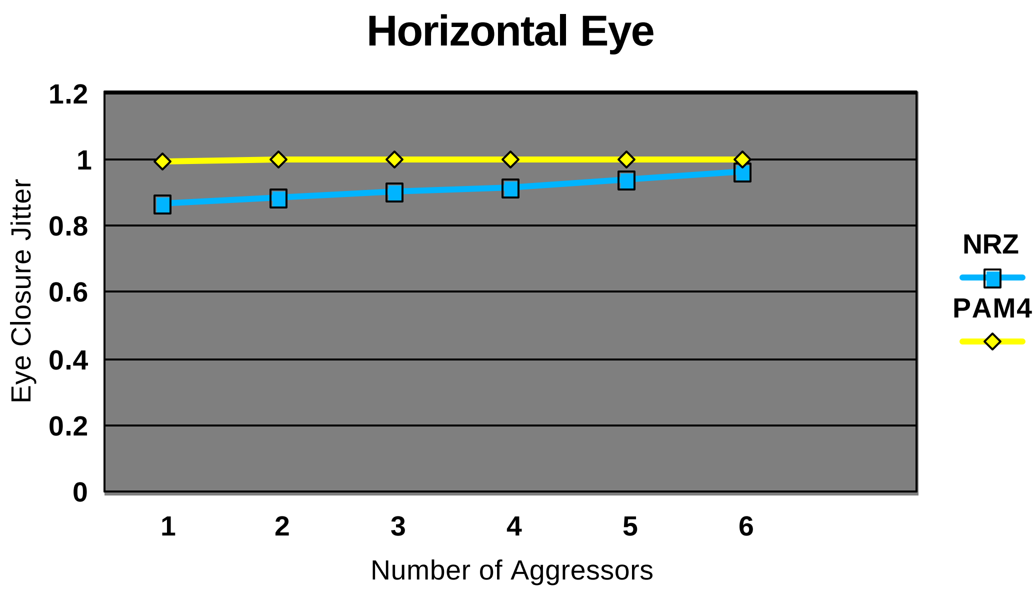
- Vertical Eye is Open for $\leq$ 2 aggressors
- Horizontal Eye is okay for $\leq$ 1 aggressors

PAM4 Eye:

- Closed

Backplane B Results





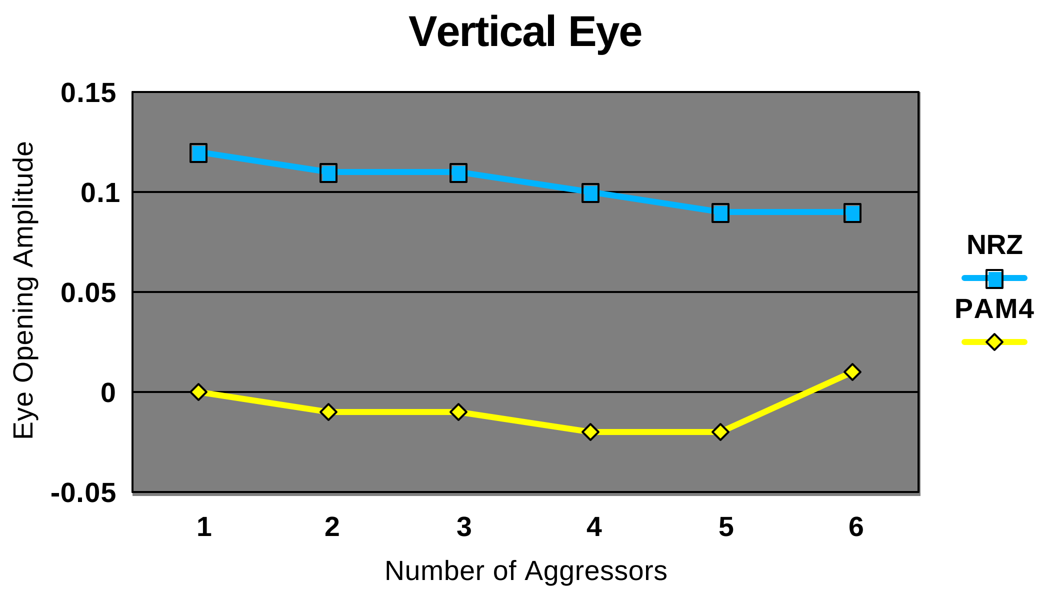
NRZ Eye:

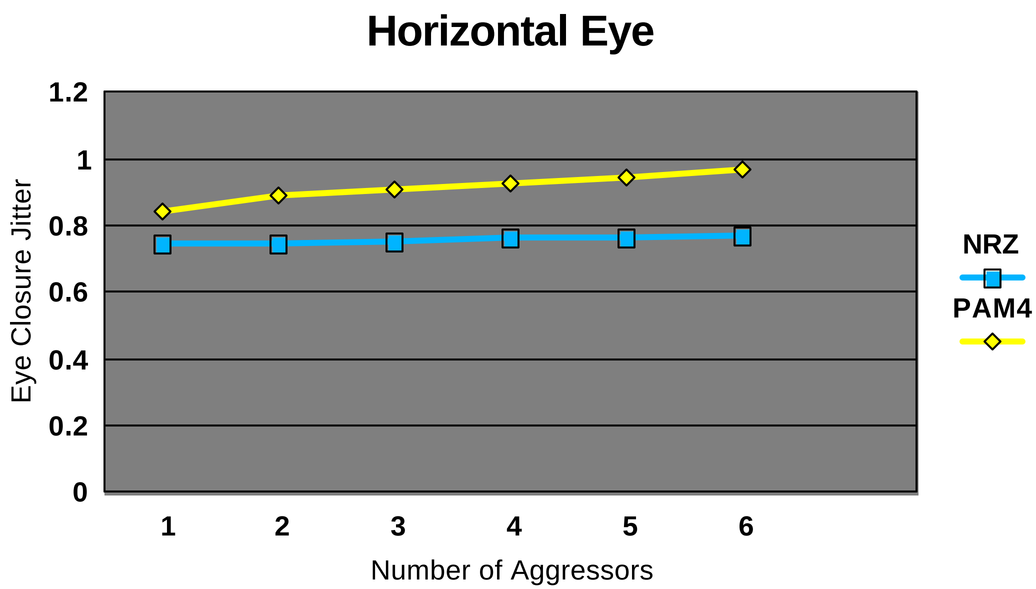
- Vertical Eye is Open
- Horizontal Eye is okay for ≤ 2 aggressors

PAM4 Eye:

- Closed

Backplane C Results





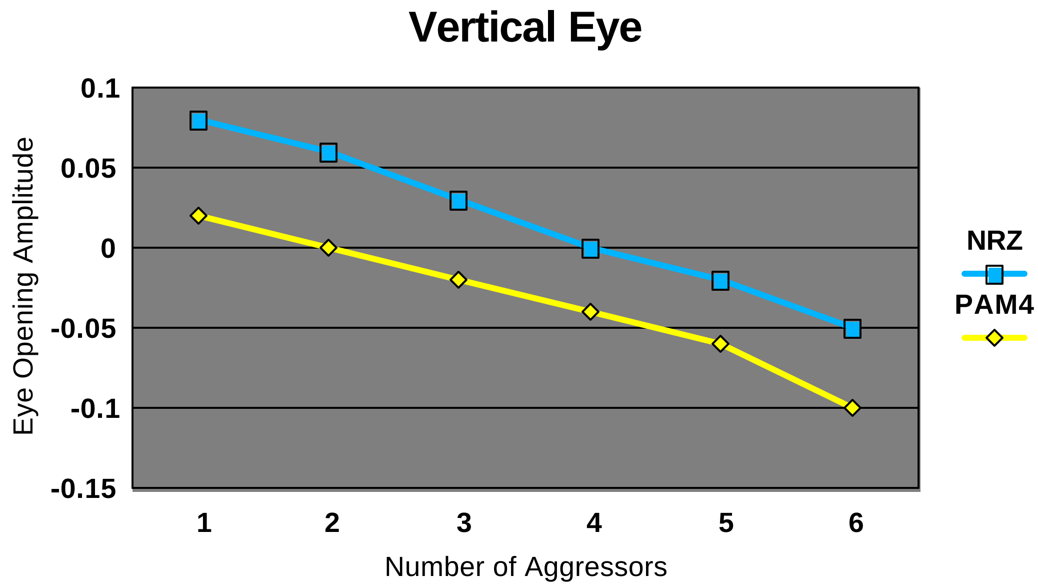
NRZ Eye:

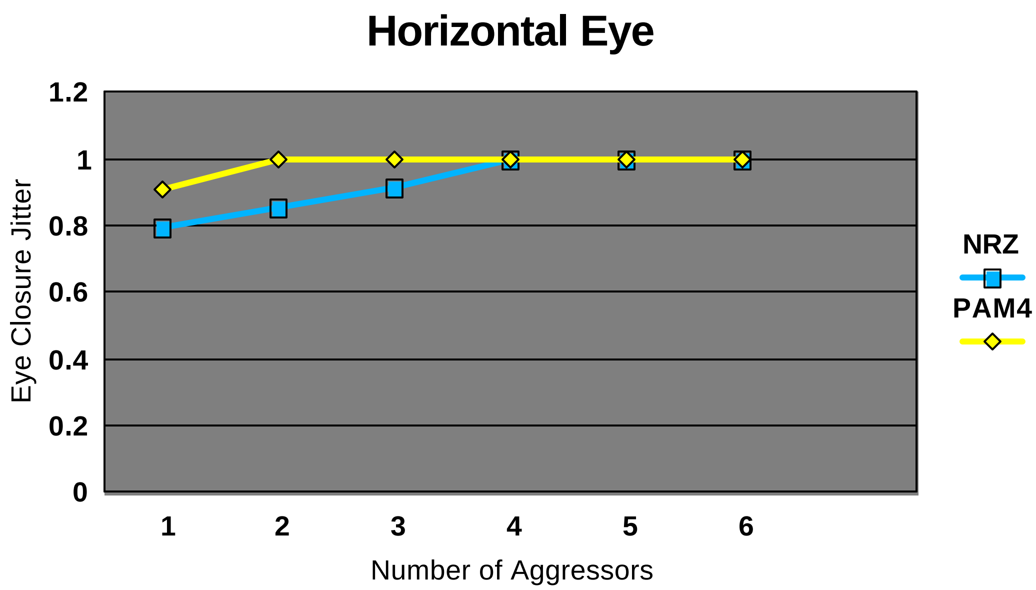
- Vertical Eye is Open
- Horizontal Eye is okay

PAM4 Eye:

- Closed

Backplane D Results





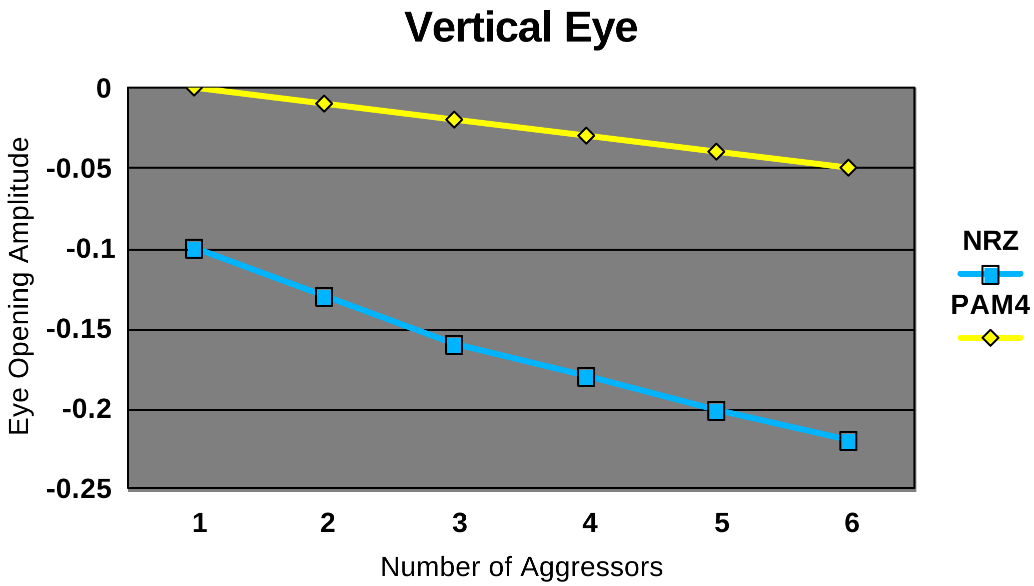
NRZ Eye:

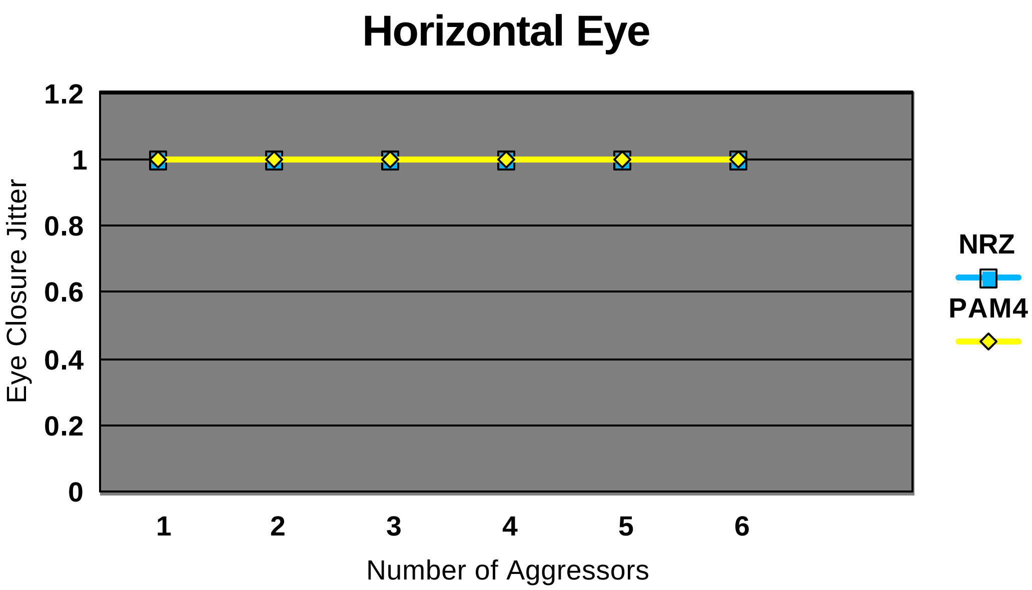
- Vertical Eye is Open for $\leq$ 3 aggressors
- Horizontal Eye is okay for $\leq$ 2 aggressors

PAM4 Eye:

- Closed

Backplane E (Legacy Case) Results





NRZ Eye:
- Closed

PAM4 Eye:
- Closed

Conclusions

- **PAM-4 does not have a demonstrated performance advantage over NRZ for this set of backplanes.**
  - ***PAM-4 is not a magic bullet to achieve legacy support.***
- **PAM-4 will perform better or worse than NRZ based on channel design factors. The results show NRZ performed better for the five backplanes being measured.**
  - **Backplanes A, B, C, and D passed NRZ with at least 1 aggressor and all of these failed to pass PAM-4 even with 0 aggressors.**
  - **Backplane C passes NRZ with 6 aggressors, but fails to pass PAM-4 even for 0 aggressors.**
  - **Only Backplane E failed to pass NRZ; it also failed to pass PAM-4.**

Conclusions

- For the channels examined, NRZ provided better results.
- PAM-4 has an advantage for very high loss channels (such as cables), however this advantage is not universal.
- Existing PAM-4 implementations use techniques such as coding or higher transmit amplitude to overcome limitations of the PAM-4 signalling.
  - Similar techniques can be applied to NRZ signalling.
  - When comparing signalling methods, care must be taken to ensure advantages/disadvantages are attributable to the signalling method and not to other factors.
- Given no clear-cut advantage of PAM-4, incumbent NRZ signalling methods should be pursued.

References

[1] More information on the Unified 10Gbps Physical Layer Initiative can be found at www.uxpi.org.

[2] "Channel Compliance Testing Utilizing Novel Statistical Eye Methodology", Anthony Sanders, Mike Resso, and John D'Ambrosia, DesignCon West 2004.